CONSTRUCTION AND COMMISSIONING OF THE HIRFL-CSR*

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Abstract

CSR is a new ion cooler-storage-ring system in China IMP, it consists of a main ring (CSRm) and an experimental ring (CSRe). The two existing cyclotrons SFC (K=69) and SSC (K=450) of the Heavy Ion Research Facility in Lanzhou (HIRFL) will be used as its injector system. The heavy ion beams from HIRFL will be first injected into CSRm, accompanying with the accumulation, e-cooling and acceleration, finally extracted to CSRe for many internal-target experiments. In 2005 the main construction of the CSR project was finished, and from that the preliminary commissioning of CSRm was started, including the first turn commissioning as a beam line, the stripping injection, and the zero-bumping orbit test, fixed-bumping orbit test with four in-dipole coils, bumping orbit test, C-beam accumulation and the investigation of the closed orbit with BPM. And now the correction of closed orbit, e-cooling and ramping test are just on going.

INTRODUCTION

From 1996 to 1998, a new ion accelerator plan was proposed [1] to upgrade the HIRFL with a multi-functional Cooling Storage Ring (CSR) forming an HIRFL-CSR accelerator system shown in Fig. 1. This will greatly enhance the performances of IMP for those researches by using Radioactive Ion Beams (RIB) and high-Z heavy ion beams in the fields of nuclear physics and atomic physics. In July of 1998 the Chinese center government approved this proposal, and at December 10 of 1999 the CSR project was started. The period from the beginning of 2000 to the summer of 2001 was the stage of the building construction, design optimization and prototype experiments. The machine fabrication was from 2001 to 2003, and the past two years of 2004 and 2005 were used for the machine installation and subsystem tests. The period from 2006 to 2007 will be the initial commissioning stage.

PROJECT DESCRIPTIONS

Outline

CSR is a double cooling-storage-ring system with a main ring (CSRm), an experimental ring (CSRe), and a radioactive beam line (RIBLL2) to connect the two rings, shown in Fig.1. The heavy ion beams with the energy range of 7~25 MeV/u from the cyclotron SFC or the cyclotron complex SFC+SSC will be accumulated, cooled and accelerated to the high-energy range of 100~500 MeV/u in the main ring CSRm, and then extracted fast to produce radioactive ion beams (RIBs) or highly charged heavy ions (high-Z beams). Those secondary beams will be accepted and stored or decelerated by the experimental ring CSRe for many internal-target experiments or high precision spectroscopy with beam cooling. On the other hand, the beams with the energy range of 100~1000MeV/u will also be extracted from CSRm by using slow extraction or fast extraction for many external-target experiments, and for the future development, the possibility of internal-target mode in CSRm was reserved for those high-energy proton experiments with the energy range of 2~2.8GeV.

Two electron coolers located in the long straight sections of CSRm and CSRe, respectively, will be used for beam accumulation and cooling.

The beam parameters and the major machine parameters of CSR are listed in table 1.

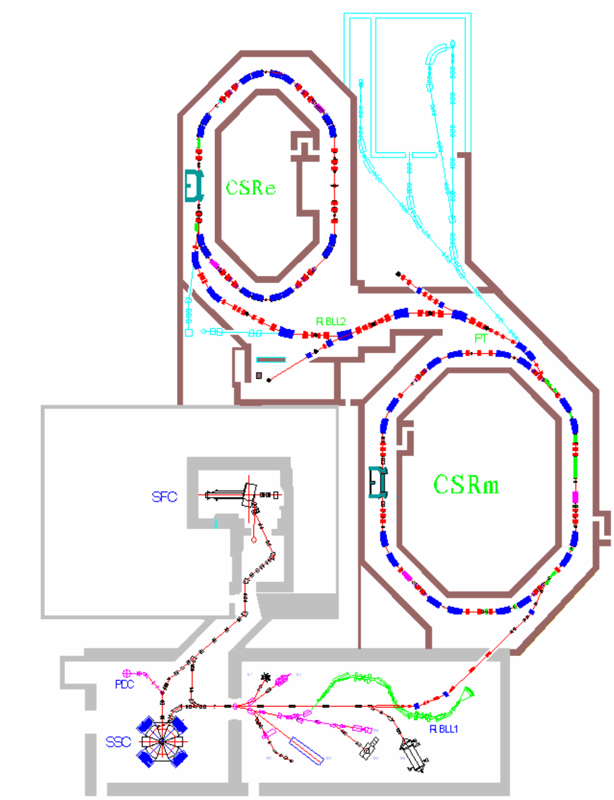

Figure 1: Overall layout of HIRFL-CSR.

Normal Operation Mode

CSR is a double ring system. The accumulation duration of CSRm is about 10s. Considering the ramping rate of magnetic field in the dipole magnets to be

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Table 1 Major parameters of the CSR

	CSRm	CSRe
Outline		
Circumference (m)	161.00	128.80
$B\rho_{max}$ (Tm)	12.05	9.40
B_{max} (T)	1.6	1.6
Ramping rate (T/s)	0.1--0.4	0.1--0.4
Beams		
Ion species	Stable nuclei: p -- U, RIBs: A<238	Stable nuclei: p -- U, RIBs :A<238
Max. energy (MeV/u)	2800(p), 1100 (C^{6+}), 500 (U^{72+})	2000(p), 750 (C^{6+}), 500 (U^{90+})
Intensity (Particles)	10^6---10^9 (stable nuclei)	$10^{3\text{--}9}$ (stable nuclei, RIBs)
Lattice	Fast extraction mode	Normal mode
Transition gamma	γ_{tr} = 5.418	γ_{tr} = 2.629
Tune values	Q_x / Q_y = 3.64 / 2.61	Q_x / Q_y = 2.53 / 2.57
Max. β (m)	β_x/β_y =15.3/30.5	β_x/β_y =30.9/22.3
Dispersion (m)	$D_{max(x)}$=5.4 (β_x=9.9)	$D_{max(x)}$=7.8 (β_x=16.0)
Acceptance		
A_h (π mm-mrad)	200 (ΔP/P = ±0.15 %)	150 (ΔP/P = ±0.5%)
A_v (π mm-mrad)	40	75
ΔP/P (%)	1.4 (ε_h= 50 π mm-mrad)	2.6 (ε_h= 10 π mm-mrad)
Subsystem		
E-cooler		
Ion energy (MeV/u)	7---50	10---500
Length (m)	4.0	4.0
RF system	Acceleration Accumulation	Capture
Harmonic number	1, 2 16, 32, 64	1, 2
f_{min}/f_{max} (MHz)	0.24 / 1.81 6.0 / 14.0	0.4 / 2.0
Voltages (n × kV)	1 × 7.0 1 × 20.0	2 × 10.0
Vacuum pressure (mbar)	3.0×10^{-11}	3.0×10^{-11}

0.1~0.4T/s, the acceleration time of CSRm will be nearly 3s. Thus, the operation cycle is about 17s. The experimental ring (CSRe) can obtain the beams once for every operation cycle.

In CSRe, two operation modes will be adopted. One is the storage mode used for internal-target experiments or high precision spectroscopy with electron cooling. Another one is the deceleration-storage mode used for atomic-physics experiments. Fig. 2 shows the magnetic field exciting procedure of the two rings.

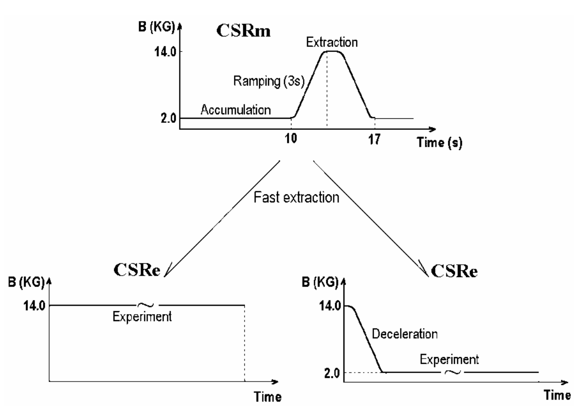

Figure 2: Magnetic field exciting procedure of CSR.

Beam Accumulation

Three modes will be used in CSRm to accumulate ions up to $10^{6\sim9}$ in a short duration of 10s. The first is the Stripping Injection (STI) for those light heavy ions (A<20) from SFC. The second is the Multiple Multi-turn Injection (MMI) in the horizontal phase space with the acceptance of 150π mm mrad for those very heavy ions (A>40) from SFC. The third one is the combination of the horizontal MMI and the RF Stacking (RFS) [3] in the momentum phase space for those heavy ions (20≤A≤40) from SFC+SSC. In the third one the horizontal acceptance is 50π mm mrad used for the multi-turn injection and the momentum acceptance is 1.25% for the RF stacking. During the accumulation, electron cooling will be used for the cooling of beam in order to increase the accumulation ratio and efficiency.

Magnets and Correlative Sub-systems

All magnet cores of CSR will be laminated of 0.5mm-thick sheets of electro-technical steel with high induction and cold-rolled isotropy. Coils will be made of T2 copper conductor with hollow and insulated with polyimide stick tape and vacuum epoxy resin impregnating. In order to reach the necessary field uniformity at the different levels of the range of 1000Gs ~ 16000Gs, a so-called modified H-type dipole was designed for CSRm. In CSRe the C-type dipole with large useful aperture will be adopt for physics experiments.

All power supplies of the ring magnets need DC and pulse operation modes, and high current stability, low current ripple and good dynamic characteristic were required. Two types of supply, traditional multi-phase thyristor rectifier for dipoles and switching mode converter for quadruples, were adopted. Table 4 is the major parameters of magnets and its correlative power supplies and vacuum chambers.

Table 2 Major correlative parameters of the magnets

	CSRm	CSRe
Dipole		
Number×angle (deg.)	16×22.5	16×22.5
Bending radius (m)	7.6	6.0
Field range (T)	0.1--1.4	0.1--1.4
Ramping rate (T/s)	0.1--0.4	0.1--0.4
Air gap (mm)	80	84
Useful aperture (mm^2)	140×60	220×70
Homogeneity (ΔB/B)	$\pm1.5\times10^{-4}$	$\pm1.5\times10^{-4}$
Vacuum Chamber		
Inner aperture (mm^2)	156×61	236×70
Cross section	Rectangular	Rectangular
Supply of dipole		
Number	1	1
Feeding mode	Series	Series
Stability (at low cur.)	$\pm1\times10^{-4}$/8h	$\pm1\times10^{-4}$/8h
Ripple (at low cur.)	5×10^{-5}	5×10^{-5}
Tracking precision	$\pm3\times10^{-4}$	$\pm3\times10^{-4}$
Quadruple		
Number	30	22
Gradient range (T/m)	0.3—10.0	0.3—6.5
Bore diameter (mm)	170	240
Useful aperture (mm^2)	160×100	280×140
ΔK/K	$\pm1.5\times10^{-3}$	$\pm1.5\times10^{-3}$
Ideal length (m)	0.5, 0.65	0.65, 0.75
Vacuum. Chamber		
Aperture (mm^2)	180×110	285×150
Cross section	Octagonal	Octagonal
Supply of quadruple		
Number	30	22
Feeding mode	Independent	Independent
Stability (at low cur.)	$\pm1\times10^{-4}$/8h	$\pm1\times10^{-4}$/8h
Ripple (at low cur.)	5×10^{-5}	5×10^{-5}
Tracking precision	$\pm5\times10^{-4}$	$\pm5\times10^{-4}$

INITIAL COMMISSIONING OF CSRM

Subsystem Tests

The construction and installation of the two storage rings were finished in the end of 2004. Since that time many offline tests have been done. For example, e-cooler, RF station, power supply, Ultra-high vacuum, magnetic field measurement and ring alignment, etc. For the e-cooler, the hollow electron beam can be obtained to partially solve the problems due to space charge effect and reduce the effect of recombination between the ions and the e-beam. In CSRm the vacuum pressure already reached to 5×10^{-12} mbar.

First Beam Storage in CSRm

In the beginning of 2006, the main ring CSRm was under the preliminary commissioning. At January 18 of 2006, the single-turn stripping injection beam of C^{6+}-6.89MeV/u was stored successfully in CSRm with bumping orbit. Fig. 3 is the stored beam signal from a BPM. In this case the RF system of CSRm wasn't used, thus the bunched beam from the cyclotron SFC would be become as a costing beam gradually after the single-turn injection, and the beam signal from BPM also became weak turn by turn.

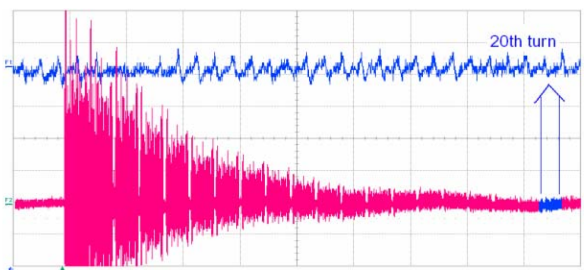

Figure 3: The stored beam signal from BPM.

From the result of the Fig.3, we can see that the beam signal of the 20th turn had already become very weak.

Based on the single-turn beam storage, at January 23 of 2006, the multi-turn stripping injection beam of C^{6+}-6.89MeV/u was stored successfully in CSRm with bumping orbit. Fig. 4 is the stored beam signal from the spectrum analyser connected with a BPM in the zero-span mode.

Figure 4: The stored beam signal from the spectrum analyser with 5 times of RF modulating.

In order to observe the stored beam signal from BPM in a long time, the stored costing beam should be re-bunched by the RF system of CSRm with the harmonic number of 4 and the RF voltage of 1.3KV. By the RF modulating, the stored beam signal can be obtained from the spectrum analyser connected with a BPM in the zero-span mode. As the showing in Fig. 4, after the multi-turn stripping injection, the stored beam was modulated by RF five times in 10 seconds. The first modulating period was 1 second, and after that every period was 0.5

seconds. According to Fig. 4, the 1/e life time of stored beam was about 10 seconds.

Preliminary Beam Accumulation of CSRm

In the spring of 2006, the new controller DSP developed by ourselves was used in the power supply control system of dipole, quadruple, bump and RF system. By using this new DSP, the synchronous times between the dynamic bumping orbit which used to cross the stripper, the period of injection beam and the RF system can be controlled accurately. Fig. 5 is the synchronous signal between RF, bumping orbit and injection beam.

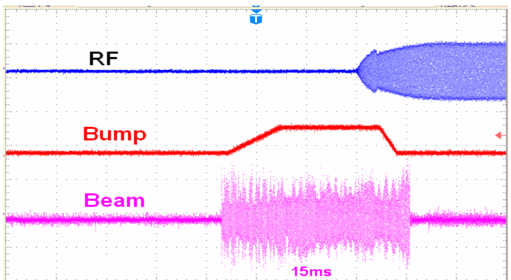

Figure 5: The synchronous signal between RF, bumping orbit and injection beam.

At April 20 of 2006, just after the bumping injection with the accumulation period of 15ms, the RF system switched on to capture the stored beam. In this case, the accumulated beam of C^{6+}-7.185MeV/u with a high intensity can be observed on the spectrum analyser. Fig. 6 is the stored beam signal from the spectrum analyser in the 5 seconds of RF modulation.

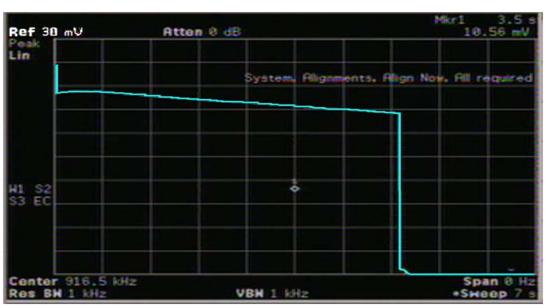

Figure 6: The stored beam signal from the spectrum analyser just after the bumping injection.

As the results shown in Fig. 6, the 1/e beam life-time is about 37 seconds with the RF capture in the first second, and the beam intensity is about 100eμA.

First Ramping Test of CSRm

In May of 2006, the dynamic scale for all quadruple power supplies was finished. After that a short acceleration test was done. In the test, the C^{6+} beam energy was increased from 7MeV/u to 14MeV/u. Fig.7 is the exciting currents of dipoles and quadruples, the RF voltage and frequency during the ramping test.

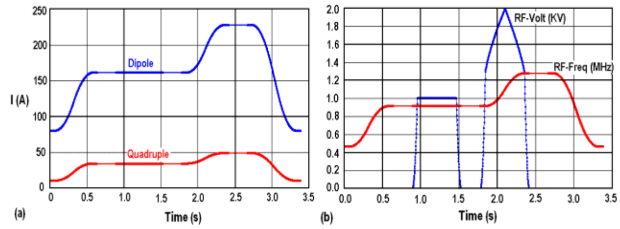

Figure 7: (a) The exciting currents of dipole and quadruple, (b) The curves of RF voltage and frequency.

The short ramping test consists of two steps, the first step is the ramping injection, and the second one is the accelerating. At June 16 of 2006, the first accelerated beam-signal was observed on the spectrum analyser with a wide-band range of 300 KHz. Fig.8 shows the beam signal of the ramping injection and acceleration from the spectrum analyser during the acceleration test.

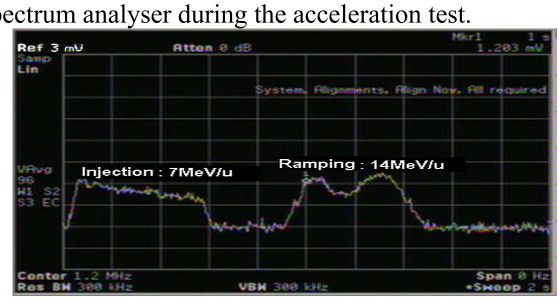

Figure 8: The beam signal of the acceleration test.

DCCT Diagnosis for the Beam Accumulation

In the summer of 2006, the new DCCT device was used to measure the beam current in CSRm. With this powerful diagnosis, the adjusting of the injection match orbit and the preliminary closed orbit correction can be done carefully. At June 29 of 2006, the accumulated beam current was first exceeded 200μA for the beam of C^{6+}-7MeV/u. Fig. 9 is the DCCT current signal for the stored beam in CSRm.

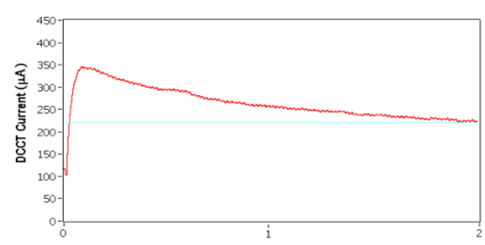

Figure 9: DCCT current of the stored beam in CSRm.

First Tune Measurement and Modification

In the autumn of 2006, the tune value of the machine can be measured first, and the initial tune (Q_x/Q_y) of CSRm is 3.44/2.75 that is far from the design value of 3.64/2.61. According to the analysis, this large tune shift was caused by the reason of the hysteresis of quadruple fields. After the modifying of the quadruple-field data, the machine tune was adjusted to the original design value, and the 1/e beam life-time in the first 3 seconds was became longer from 4s to 15s. Fig. 10 shows the stored beam with the tune value of 3.610/2.637.

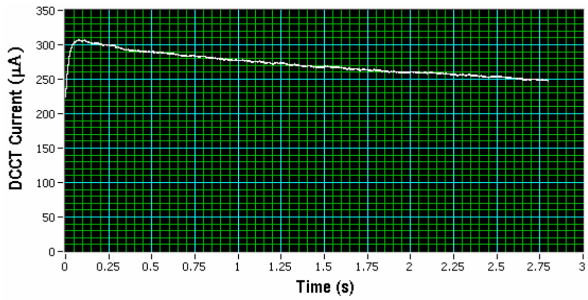

Figure 10: The stored beam with the tune of 3.610/2.637.

1GeV/u Ramping Commissioning

After the modification of tune value, the high energy acceleration experiment from 7MeV/u to 1000MeV/u for C^{6+} ions was done. Fig. 11 is the energy curve, the curves of RF voltage and frequency, and the exciting currents of dipoles and quadruples during the whole ramping period.

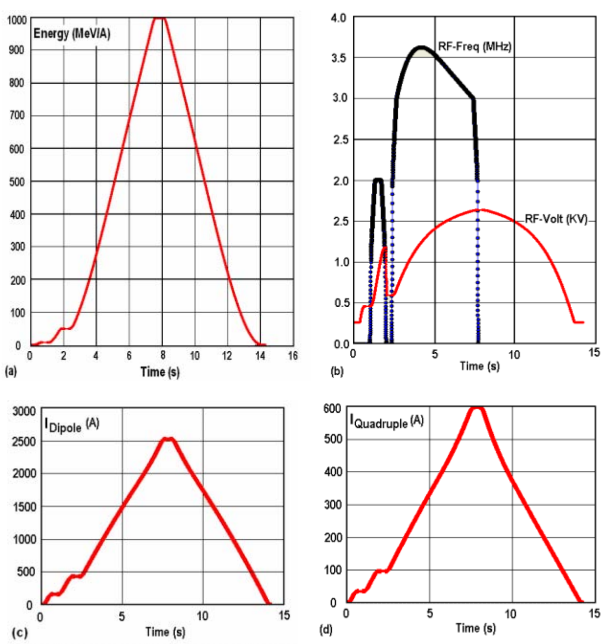

Figure 11: Curves of energy, RF and exciting currents during the ramping period from 7MeV/u to 1GeV/u.

During the 1GeV/u acceleration, the C^{6+} beam, which was injected by stripping injection from the small cyclotron SFC, will be accelerated from 7MeV/u to 1GeV/u, the magnetic rigidity of beam will be changed from 0.76T.m to 11.3T.m, the dipole field will be increased from 0.1T to 1.5T accompanying with the exciting current of power supply from 160A to 2500A, and the exciting currents of the 30 quadruples will be raised from nearly 20A to about 600A respectively.

For the 1GeV/u ramping, the RF harmonic number of frequency should be changed from 2 to 1 at the energy of 50MeV/u. Because the frequency region of the CSRm RF system is 0.25~1.7MHz, but the revolution frequency of the beam at the injection energy of 7MeV/u is only 0.227MHz, this can't reach to low limit of the frequency region. So, in the low energy section of the acceleration, the harmonic number of RF is adopted as 2, and the start frequency is 0.454MHz. After 50MeV/u the revolution frequency is more than 0.586MHz, than the harmonic number can be changed to 1 until the final energy of 1GeV/u. Fig. 12 shows the beam current during the 1GeV/u ramping.

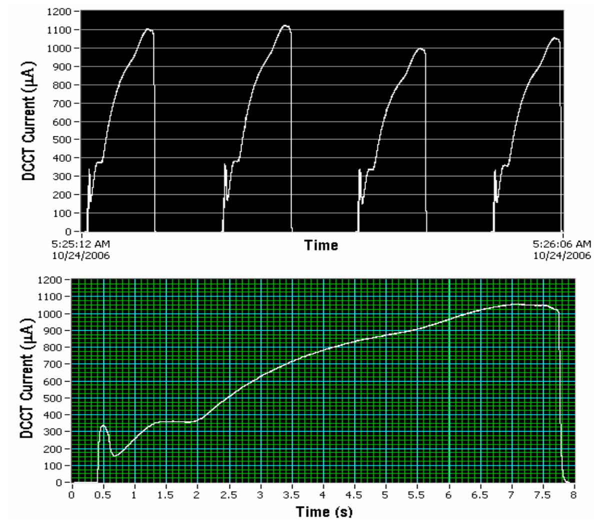

Figure 12: The beam current during the 1GeV/u ramping.

For the 1GeV/u acceleration, the whole ramping time is about 8s, including 200ms for the stripping injection, 200ms for the harmonic number changing, and 200ms for the 1GeV/u top. The whole acceleration efficiency of the beam is more than 90%, and in the final 1GeV/u top, the beam current also can be reach to 1mA, namely the particle number of the C^{6+} ions with the energy of 1GeV/u is more than 5×10^8 in CSRm.

Commissioning Schedule of CSR

Before the summer of next year, the fast extraction, COC, e-cooling, and multiple multi-turn injection will be done in CSRm, and after that the second ring CSRe can obtain the first beam. The whole initial commissioning of CSR will be finished in the end of 2007.

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